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2005 J. Phys. G: Nucl. Part. Phys. 31 S1577

(http://iopscience.iop.org/0954-3899/31/10/036)

INSTITUTE OF PHYSICS PUBLISHING JOURNAL OF PHYSICS G: NUCLEAR AND PARTICLE PHYSICS

J. Phys. G: Nucl. Part. Phys. **31** (2005) S1577–S1582 doi:10.1088/0954-3899/31/10/036

Nuclear structure of the odd–odd nucleus ^{58}Co

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Received 16 March 2005
Published 12 September 2005
Online at stacks.iop.org/JPhysG/31/S1577

Abstract

The odd–odd ^{58}Co nucleus has been studied with the ^{51}V(^{10}B, p2n) reaction at 33 MeV and 36 MeV incident energy using the γ-spectrometer Saci-Pererê. Excited states up to 8.0 MeV and spin up to 11^+ have been observed. DSAM lifetimes for 13 excited states were measured. The results are compared to shell model calculations using the GXPF1 effective interaction, developed for use in the fp shell.

1. Introduction

Nuclei close to doubly magic shell closures have been the object of extensive experimental and theoretical investigations [1–3]. Spectroscopic data from these nuclei provide essential information for the parameter sets of spherical shell model calculations and apply severe constraints on the outcome of such calculations and, consequently, define the effective nuclear forces. At the $N = Z = 28$ shell closure, the gap is relatively small so that particle–hole excitations across it have relatively low energies. For shell model calculations around this magic number, ^{56}Ni has often been assumed as an inert core. However, it has been shown that this core is rather soft and only a very limited description is provided by the closed-shell model for the magic number 28 [4]. These structures were successfully described for N or $Z = 28$ nuclei only after considering the existence of significant core-excitations in low-lying non-yrast states as well as in high-spin yrast states [3].

In this study, we present new results on excited states of ^{58}Co, thus enriching the systematics of the nuclear structure along the $N = 31$ chain. This nucleus has three particles and one hole coupled to the ^{56}Ni core and has been studied so far with proton and α particle induced reactions [5–7]. Therefore, very little was known regarding its high-spin structure.

2. Experimental procedure

The ^{58}Co nuclei were produced with the fusion–evaporation reaction ^{51}V(^{10}B, p2n) at 33 MeV bombarding energy, with the 8 MV Pelletron accelerator of the University of São Paulo (USP). The target consisted of a stack of three self-supporting natural ^{51}V foils of 200 μg cm^{-2}. For DSAM lifetime measurements the same reaction was used at 36 MeV beam energy with a 0.77 mg cm^{-2} ^{51}V foil on Pb backing. Gamma–gamma-charged particle coincidences were measured with the Saci–Pererê γ-ray spectrometer. Saci [8] (*Sistema Ancilar de Cintiladores*) is a 4π-charged particle system consisting of 11 plastic phoswich scintillator $\triangle E$–E telescopes. Pererê [9] (*Pequeno Espectrômetro de Radiação Eletromagnética com Rejeição de Espalhamento*) is a γ-array spectrometer composed of four GeHP detectors with BGO Compton shields. Two Compton suppressed GeHP detectors were placed at 37° and two at 101° with respect to the beam direction. Events were collected when at least two HPGe detectors fired in coincidence. A total of 48×10^6 Compton suppressed γ–γ events were collected for the thin target experiment and about 20×10^6 for the thick target experiment. γ-ray energy and efficiency calibrations were made with ^{56}Co,^{133}Ba and ^{152}Eu sources. The thin target data have been Doppler corrected and sorted into symmetrized γ–γ, and proton-gated γ–γ matrices. Background-subtracted spectra generated from these matrices were used to construct the level scheme of ^{58}Co using the Radware software package [10]. The γ-ray transitions belonging to ^{58}Co were identified by setting gates on 1p charged particle fold. γ-rays from ^{57}Co, which is the main contaminant channel in the 1p-gated spectra, were identified from previous work [11]. The assignment of the spins to the ^{58}Co levels was based on the DCO ratios. We have assumed only positive parity states since the shell model does not predict negative parity states in ^{58}Co within the excitation energy and spin limits of this work. In order to effect the lifetime analysis, data were sorted into two γ–γ matrices having on the first axis the detectors at 37° and 101°, respectively, and on the second axis, any of the other three detectors. We used the LINESHAPE code to extract the lifetimes of the excited states [12]. This code was modified in order to include the recoil spread due to particle emission [13]. The Northcliffe–Schilling parametrization corrected for atomic shell effects was adopted for the electronic stopping power [14].

3. Experimental results

The level scheme extending up to an excitation energy of about 8.0 MeV and spin $I^\pi = 11^+$ has been proposed based on the coincidence relationships, intensity balance on each level, and energy sums from different paths using the 1p-gated matrix (see figure 1). A total of 47 new γ-transitions de-populating 37 new excited states were observed. The level energies are referred to the low-lying 2^+ state previously known [15]. In figure 2 an example of a gated γ spectrum, obtained from the γ–γ matrix, is shown. Thirteen DSAM lifetimes were determined. Two examples of lineshape analysis for transitions depopulating the excited levels are displayed in figure 3.

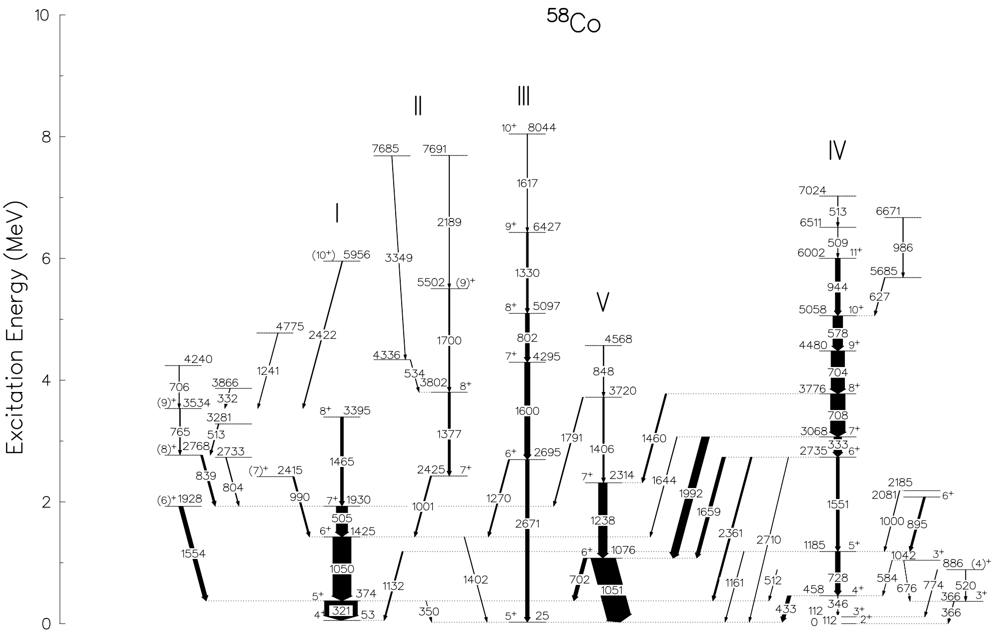

Figure 1. Experimental decay scheme of the nucleus ^{58}Co deduced from the present work. The γ-ray energies are indicated in keV.

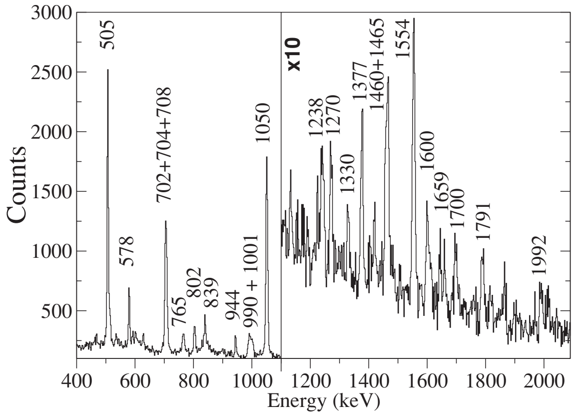

Figure 2. γ-ray spectrum in coincidence with the 321 keV transition and with one proton.

4. Shell model calculations

In order to understand the observed structure, spherical shell model calculations have been performed with the MSHELL [16] and Antoine codes [17]. We have used the model space and the residual interaction named GXPF1, developed for the description of fp-nuclei [3, 18]. The calculation with the GXPF1 interaction was performed in the full fp shell with up to eight particle excitations from the $1f_{7/2}$ orbital to the $1p_{3/2}$, $1f_{5/2}$ and $1p_{1/2}$ orbitals. Both shell model codes produced very similar results [19]. In order to achieve correspondence between

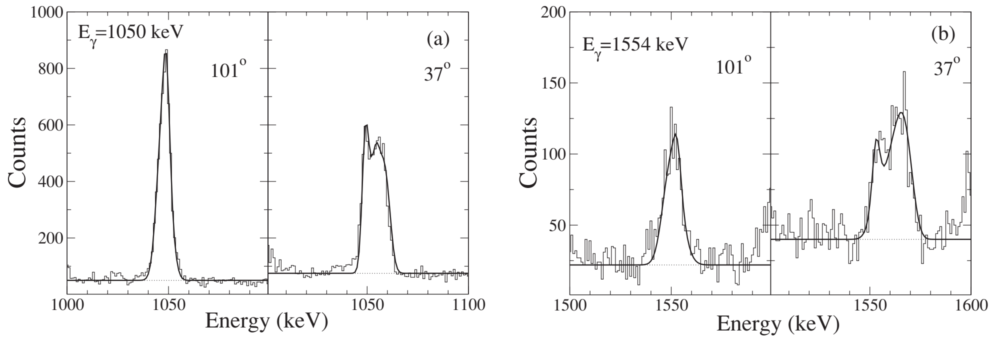

Figure 3. (a) Lineshape analysis for the $6_2^+ \rightarrow 5_2^+$ 1050 keV transition and (b) $(6)^+ \rightarrow 5_2^+$ 1554 keV when gated on 321 keV transition, observed at 101° and 37°.

Table 1. Spin-parity, experimental and theoretical excitation energies, γ-ray energies, branching ratios, experimental and theoretical lifetimes and experimental and theoretical B(M1) values for ^{58}Co. The theoretical values were extracted from the results of the Antoine code, performed up to the third excited state for each spin. The B(M1) values are in μ_N^2.

J^π	E_x (keV) (experiment)	E (keV) (theory)	E_γ (keV)	BR (experiment)	τ (ps) (experiment)	τ (ps) (theory)	B (M1) (experiment)	B (M1) (theory)
6_1^+	1076.0(9)	1092	1050.9(1)	86.6(12)	<0.1	0.12	>0.42	0.32
			702.1(2)	13.4(8)			>0.22	0.13
5_3^+	1185.3(9)	1313	727.63(7)	73.2(9)	0.14(2)[a]	0.10	0.76(11)	0.42
			1131.9(4)	20(2)			0.055(9)	0.08
			1161(1)	7(2)			0.018(5)	0.05
6_2^+	1424.7(9)	1528	1050.4(1)	97.4(1)	0.11(3)	0.08	0.43(11)	0.36
			1402(2)	2.6(10)			0.005(2)	0.05
7_1^+	1929.8(9)	1993	505.13(5)	100	0.3(1)	0.57	1.5(5)	0.71
$(6)^+$	1928.3(12)		1554.0(2)	100	0.42(5)		0.036(4)	
7_2^+	2314(1)	2440	1237.6(1)	100	$0.23^{+0.08}_{-0.10}$	0.03	$0.13^{+0.05}_{-0.06}$	0.70
6_3^+	2735.2(9)	2235	1550.7(1)	35.2(13)	0.25(10)	0.07	0.021(8)	0.46
			1659.2(1)	40.2(14)			0.020(8)	0.00
			2361.0(2)	20.5(10)			0.0035(14)	0.01
			2710(1)	4.1(8)			0.0005(2)	0.02
7_4^+	3068.2(9)		333.06(4)	48.8(12)	$0.11^{+0.04}_{-0.01}$			
			1644.2(6)	3.5(4)				
			1991.9(1)	47.7(12)				
8_1^+	3395(1)	3478	1464.8(2)	100	0.10(6)	0.03	0.18(11)	0.42
8_4^+	3775.7(9)		707.53(5)	89.9(3)	0.11(1)		1.29(12)	
			1460.5(3)	10.1(6)			0.0017(2)	
9_1^+	4480(1)		704.0(1)	100	0.11(1)		1.47(13)	
10_1^+	5058(1)		578.35(4)	100	0.136(14)		2.14(22)	
11_1^+	6002(1)		943.95(7)	100	0.090(9)		0.74(7)	

[a] ($\tau = 0.20^{+0.09}_{-0.06}$ ps; $\tau = 0.24^{+0.11}_{-0.07}$ ps) [15].

a predicted and a detected level, it is necessary that both the level energies and the decay patterns be in fair agreement. The theoretical calculations for the branching ratios give an idea of which transitions should be considered most important. The shell model calculations with MSHELL compare reasonably well with 19 excited states in the first four sequences, taking into account the free nucleon g-factors and effective charges $q^{\pi}_{\rm eff} = 1.23$ and $q^{\nu}_{\rm eff} = 0.54$. For the seven lowest yrast levels, including the g.s., the largest disagreement is for the 3^+ level at 112 keV instead of the 256 keV prediction. A majority of the levels with spin up to 8^+ in three non-yrast sequences exhibited discrepancies between predicted and measured energies of less than 100 keV. The only exceptions are the 6^+_3 and 8^+_4 states with differences of 526 and 281 keV, respectively. However their correspondence with the experimental levels is less certain because of the difference in the predicted branching ratios. Although these states are very mixed, the dominant configuration is $\pi \mathrm{f}^{-1}_{7/2} \otimes \nu\left(\mathrm{p}^2_{3/2}\mathrm{f}^1_{5/2}\right)$. In table 1 the lifetimes for 13 measured excited states, together with the shell model calculations using the Antoine code for those states for which correspondence is possible, are shown. We present the first three excited states for each spin. In these calculations we used effective charges $q^{\pi}_{\rm eff} = 1.5$ and $q^{\nu}_{\rm eff} = 0.5$. The lifetimes are well reproduced by the shell model calculations except for the 7^+_2 state. The correspondence for this state was done with the third calculated 7^+ state.

5. Conclusions

In conclusion, the level structure of the odd–odd ^{58}Co nucleus, populated with a heavy ion fusion–evaporation reaction, was measured for the first time. Levels up to 8 MeV and spin J = 11^+ and DSAM lifetimes of 13 excited states in ^{58}Co were measured. The shell model calculations with the GXPF1 residual interaction reproduce well the experimental levels and five lifetime values, considering the existence of significant core-excitations. The levels are characterized by high configuration mixing with a prevalence of the $\pi \mathrm{f}^{-1}_{7/2} \otimes \nu\left(\mathrm{p}^2_{3/2}\mathrm{f}^1_{5/2}\right)$ configuration. More experimental information on nuclei in the region of ^{56}Ni should provides essential information for the parameter sets of spherical shell model calculations and consequently define the effective nuclear forces.

Acknowledgments

This work was partially supported by the Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP) and the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), Brazil.

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